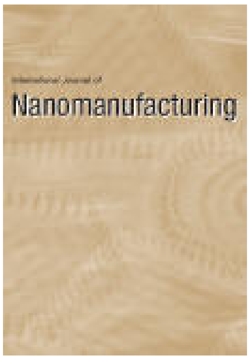

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Output characteristics test of piezo-stack actuators for driving high stiffness loads with different preload

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Abstract: Piezo-stack actuators are widely used in micro-displacement mechanisms due to their high accuracy, small size and high output force. Analysing the output characteristics of piezo-stack actuators is an important step to ensure the high precision of micro-displacement mechanism. In this paper, a test device for output characteristics of piezo-stack actuators driving high stiffness loads is designed, and a new piezo-stack actuator preload mechanism is proposed. The simulation results verify the proposed stiffness model and dynamic model of the test device. When the same preload force was applied to the piezo-stack actuators and the frequency of driving voltage increases, the displacement amplitude of the piezo-stack actuators does not change significantly, but the hysteresis loop becomes significantly larger and the hysteresis increases. When the preload force is increased with constant voltage frequency, the output displacement of the piezo-stack actuators increases significantly at first, but decreases when the preload force exceeds a certain threshold, about 20 MPa. In this case, the hysteresis loop becomes larger and the hysteresis increases.

Keywords: piezo-stack actuator; preload; high stiffness load; voltage loading rates.

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1 Introduction

Piezoelectric ceramics have a positive and negative piezoelectric effect, which enables the interconversion of mechanical and electrical energy. Piezoelectric actuators are widely used in the fields of microelectronics, medicine, aerospace and ultra-precision machining due to their high precision, small size, high bandwidth and high output force (Yong, 2016; Zhu et al., 2019; Li et al., 2021).

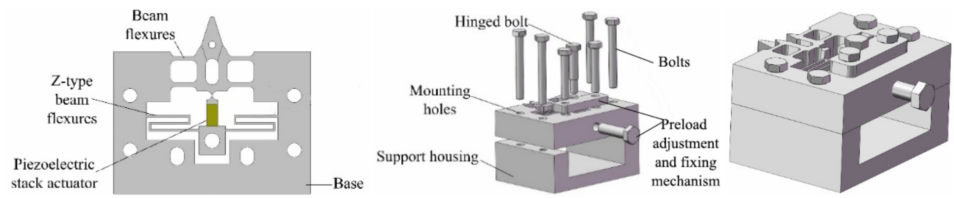
To obtain large deformation, multilayer piezoelectric ceramics are stacked together to form piezo-stack actuator. As piezo-stack actuators can only withstand pressure, in order to ensure that they can withstand a certain amount of tension, preload is applied to them to ensure that the actuator is always under pressure during operation. The study of the output characteristics of piezoelectric actuators under preload is of great importance. Zhang (2017) studied the static hysteresis characteristics and dynamic hysteresis characteristics of piezoelectric actuator without applying preload. Chen (2020) tested the piezoelectric actuator output force characteristics and analysed the voltage-force hysteresis curve of the piezoelectric actuator and found that the voltage-force hysteresis curve exhibited memory characteristics and rate dependence. The output displacement curves of piezoelectric actuators without preload, and with low load, and high load are described in the product brochure from PI Co (German) (https://www.physikinstrumente.com). It is recommended that a preload of 15 MPa and the maximum preload of 30 MPa for dynamic use of the piezoelectric actuators in the product brochure of Boshi Co. (China) (http://szbsjrrjsy.dayinmao.com). But it does not elaborate on the influence of preload on the characteristics of the piezoelectric actuators when driving high stiffness loads. Zhang et al. (2019) analyse the force output characteristics of piezoelectric actuators under different preload and different voltage frequencies, the initial load and voltage frequency can affect the repeatability and stability of the output force of piezoelectric actuator. The initial conditions of the best output are obtained.

In this paper, a new preload mechanism is proposed, and a mechanical characteristic test device with adjustable preload force is designed to study the mechanical characteristics of piezo-stack actuators under preload force, including parameters such as preload force, output displacement, hysteresis, and drive voltage frequency.

2 Materials and methods

The preloading mechanism of piezo-stack actuator is mainly composed of flexible guide mechanism, Z-shaped flexible beams and preload adjustment and fixing mechanism. Its diagram is shown in Figure 1. The flexible guide mechanism consists of four parallel beams, which provides a certain stiffness along the direction of driving displacement. And the additional straight circular flexure hinge is used to avoid uneven force on the end face of the piezo-stack actuator. The symmetrical Z-beams, which carry the piezo-stack actuator, provides a certain initial preload once the actuator is installed in place. The stiffness of the Z-beams should be small enough to facilitate the installation of the actuators. And it should also be sufficiently large to provide the requisite initial preload. A preloaded bolt is used to adjust the preload. Once the preload is applied to a certain value, a brake plate connected with Z-beams by hinge bolt is fixed on the base. The preload adjustment and fixing mechanism can avoid rear seat displacement output of the actuator during dynamic operation.

Figure 1 (a) Mechanical devices with a novel preload mechanism (b) An exploded view showing the devices and its support housing (c) Assembled view of the mechanical devices system (see online version for colours)



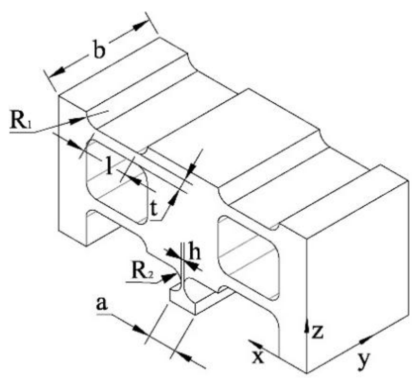
(a) (b) (c)

2.1 Design of compliant mechanism

2.1.1 Mechanical model for compliant mechanism

The flexible guide mechanism of the test device consists of four beams and one circular type flexible hinge, as shown in Figure 2.

Figure 2 Schematic of the compliant mechanism



A beam can be considered as a thin-walled beam with one end solidly supported and the other end subjected to a Z-directional force F and a counterclockwise moment M. Since the resulted displacement is on the order of micrometer, it can be considered as small deformation compared with the size of the flexible hinge. So we can ignore the chamfer and consider only the deflection and angle of rotation under the action of force F and moment M. The deflection and angle of rotation under the force and moment are obtained according to the superposition method, respectively. The equivalent stiffness of the four beams is calculated as follows:

$$k_1 = \frac{4Ebt^3}{l^3} \tag{1}$$

The tensile stiffness of a circular flexible hinge in the z-axis direction is

$$k_z = \frac{F}{\Delta x} = Eb\left[\frac{2(2s+1)}{\sqrt{4s+1}}\arctan\sqrt{4s+1} - \frac{\pi}{2}\right]^{-1} \tag{2}$$

The compliant mechanism is equivalent to two springs connected in series, with an overall stiffness of

$$k = \frac{k_1 k_z}{k_1 + k_z} \tag{3}$$

The first-order resonant frequency of the structure is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M_e}} \tag{4}$$

where M_e is the effective mass of the compliant mechanism.

After performance comparison and analysis, the final structural parameters of the compliant mechanism are shown in Table 1. From equations (1), (2), (3) and (4), the stiffness is $k = 197.4$ N/µm, and the first-order resonant frequency is $f = 7{,}371$ Hz.

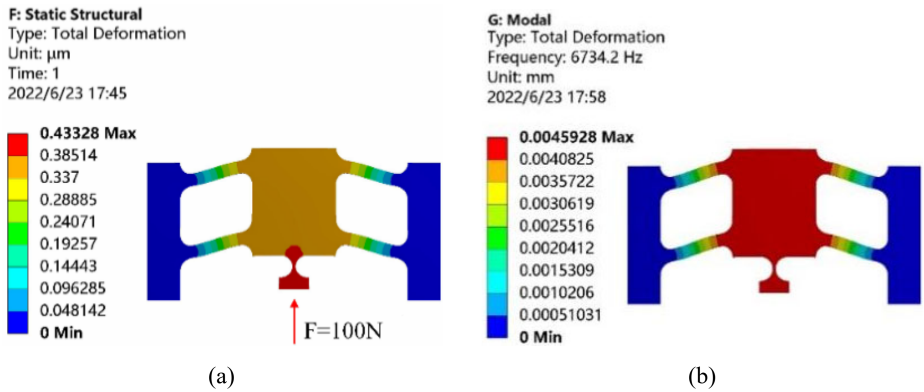
Table 1 Summary of material properties, design parameters of flexures

Parameters	*Unit*	*Value*
Young's modulus, E	GPa	196.5
Poisson's ratio, v		0.25
R_1	mm	2
l	mm	8
b	mm	20
t	mm	2
a	mm	5
R_2	mm	2
h	mm	0.5

2.1.2 Finite-element-analysis

In order to verify the performance of the designed test device, ANSYS software was used to perform finite element simulation of the static and dynamic characteristics of the designed structure. The relative error of the stiffness is 17.5%. Figure 3(b) shows the first resonant modes obtained using ANSYS, and the corresponding resonant frequency is 6,734.2 Hz, with a relative error of 8.6% with the analytical result of equation (4).

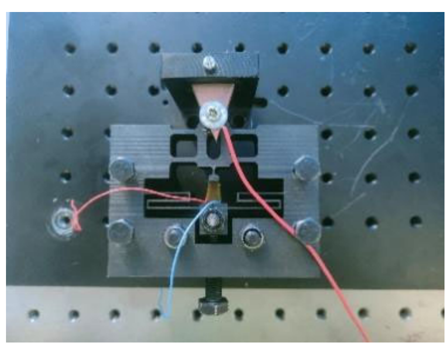
Figure 3 The results obtained by FEA, (a) stiffness estimation of the mechanism (b) the first resonant model (see online version for colours)



2.2 *Experiment setup*

The preloading mechanism with piezo-stack actuator installed is shown in Figure 4. The actuator is driven by a commercially available piezoelectric controller (E01.D2 from Coremorrow Co.). And the displacement of the actuating end of the preloading mechanism is measured by a capacitive displacement sensor (CS02 capacitive sensor from MICRO-EPSILON Co, German), which has a bandwidth of 5,000 Hz and a resolution of 20 nm. The generation of voltage control signal and the acquisition of output displacement signal are realised by NI data acquisition card and programs based on Labview software.

Figure 4 Photograph of the preloading mechanism (see online version for colours)



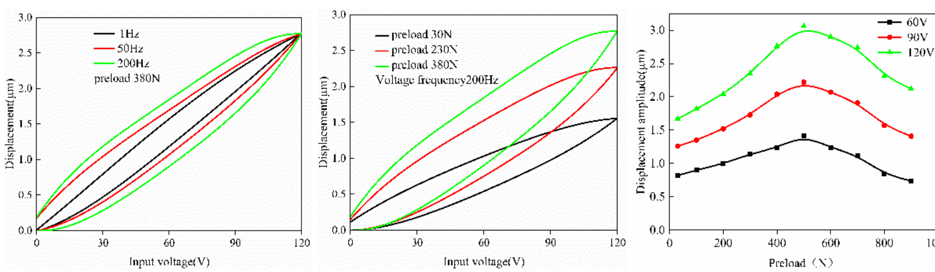
3 Results and discussion

When the preload force applied on the piezo-stack actuator remains unchanged, sinusoidal driving voltage (the amplitude is 120 V) with frequencies of 1 Hz, 50 Hz and 200 Hz is applied to the piez-stack actuator, respectively. And the output displacement signals are measured. Figure 5(a) shows the displacement-voltage curves of the piezo-stack actuators under different input frequencies. It can be seen that as the voltage frequency increases, the displacement amplitude of the piezo-stack actuators does not change significantly, but the hysteresis loop becomes significantly larger and the hysteresis increases.

A sinusoidal voltage with frequency 200 Hz and variation range 0~120 V was applied to the piezo-stack actuators, and the preload force was adjusted by the preload adjustment and fixing mechanism. Figure 5(b) shows the displacement graph of the piezo-stack actuators with the same voltage frequency and different preload forces. As the preload force increases, the output displacement of the piezo-stack actuators increases significantly, and the hysteresis loop becomes larger and the hysteresis increases.

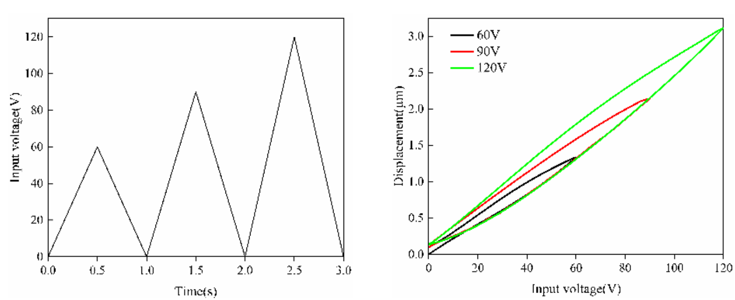
A sinusoidal voltage of 1 Hz with amplitude of 120 V was applied to the piezo-stack actuators, and the preload force is continuously adjusted to increase. A graph of displacement amplitude versus preload force was shown in Figure 5(c). When the piezo-stack actuators drive a high stiffness load, applying a certain preload force helps to increase the output displacement of the piezo-stack actuators. As the preload force increases, the output displacement of the piezo-stack actuators also gradually increases. But when the preload force exceeds a certain threshold, about 20 MPa, it will reduce the output displacement of the piezo-stack actuators.

Figure 5 Experimental performance, (a) displacement/voltage graph with the different voltage frequency and same preload (b) displacement/voltage graph with the same voltage frequency and different preload (c) relationship between preload and displacement amplitude (see online version for colours)



(a) (b) (c)

Figure 6 (a) Voltage/time graph (b) Displacement/voltage graph with different loading rates (see online version for colours)



(a) (b)

To further study the hysteresis nonlinear characteristics of the piezo-stack actuators at different voltage loading rates, a triangular voltage range of 0 to 120 V with a frequency of 1 Hz was applied to the piezo-stack actuators with an initial cycle voltage amplitude of 60 V. The amplitude was increased by a 30 V per cycle and the voltage waveform was shown in Figure 6(a). The period was the same, the amplitude was different, resulting in different loading rates of the voltage. The displacement graph of the piezo-stack actuators in this case is shown in Figure 6(b). As the amplitude of the drive voltage increases, the hysteresis of the piezo-stack actuator increases, some repetition of displacement during voltage rise.

4 Conclusions

In this paper, a mechanical device with adjustable preload was designed and machined to test the output characteristics of a piezo-stack actuator under preload，and presents the working principle, theoretical and simulation analysis results of the measuring device. The output characteristics of the piezo-stack actuator under different preload were investigated, and the relationships between output displacement, hysteresis, voltage loading rate, and preload force are given by experimental comparison. It provides a certain reference value for the practical application of piezoelectric actuators in driving high stiffness loads, and also lays the foundation for the next step of establishing an overall control system to improve the accuracy.

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